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Energy Procedia

Energy Procedia 37 (2013) 5456 – 5463

ELSEVIER

GHGT-11

Experimental Measurements of Threshold Pressure for Modeling Saline Aquifers in Japan

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Abstract

In this study we evaluated threshold pressures of fine grained rocks in Japan. We used two methods, one is indirect method and the other is direct measurement. Mercury intrusion test (MIT) is the indirect method and the relations between threshold pressures and permeability coefficients results are consistent with existing data. But the threshold pressure obtained by MIT was a little lower than that by direct measurement. The reason for this difference might be that the MIT can't take account of flow direction, though flow direction of direct measurement is perpendicular to the bedding plane. As direct method, we conducted threshold pressure measurements by stepwise way using CO2 and N2. Similar to the previous study, threshold pressure using N2 was higher than that using CO2.

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Keywords: CO2 storage; sealing effeciency; threshold pressure

1. Introduction

For safe and efficient geological storage, it is necessary to evaluate sealing efficiency of seal layers that prevent CO2 from infiltrating into the upper layers. Considering CO2 storage in saline aquifers of Japan, low permeable sediments in Plio-Pleistocene are expected as seal layers [1]. These younger sediments have larger porosities and their sealing efficiencies might be relatively lower.

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1876-6102
Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.465

There are some methods to estimate sealing efficiency of rocks in laboratory. Capillary pressure measurement by mercury intrusion test is conventional one and another one is direct measurement of threshold pressure by injecting gas to rock samples. Former method has some advantages that test is rather easy to perform and less time consuming. On the other hand, there are some disadvantages such as the volume of rock sample is very small and mercury intrusion process is not so similar to displacement process of pore fluids. Threshold pressure obtained from direct measurement method is thought to be more accurate but this method requires longer time to complete the displacement process of pore fluids.

In this study mercury intrusion test (MIT) and direct measurement of threshold pressure with gaseous N2 and supercritical CO2 were performed for estimating sealing capacity of sedimentary rocks in Japan.

2. Samples

The sedimentary rocks used in laboratory tests were taken from the Yourou valley. The Yourou valley is located in Chiba prefecture in Jjapan. Many of geological surveys have been done in this area from the viewpoint of sedimentology and there are plenty of geological data. The samples were derived from Ohtadai and Kiwada layer that belong to Kazusa formation group formed in Plio-Pleistocene. These layers mainly consist of siltstone with thin sandstone layers. In some of recent research works for CO2 storage in Japan rock samples of Ohtadai and/or Kiwada layers were widely used for experimental measurement in laboratory.

The physical properties of rock samples used in this study are shown in table 1. We chose 14 samples for testing 7samples are taken from Ohtadai layer and the other 7 samples are taken from Kiwada layer. Bulk densities of siltstone by caliper method vary between 1.433-1.555 g/cm^3 and porosities determined by buoyancy method are in the range of 41.7-45.3%. Bulk densities of silty sandstone vary between 1.483-1.608 g/cm^3 and porosities are in the range of 36.1-43.7%.

Table 1. Physical properties of rock samples

Sample No.	Layer	Rock description	Bulk density (g/cm^3)	Porosity (%)
O_1-1-2	Ohtadai	Siltstone	1.551	42.0
O_1-2-2	Ohtadai	Siltstone	1.533	41.9
O_1-3-2	Ohtadai	Siltstone	1.555	41.7
O_2-2-3	Ohtadai	Siltstone	1.497	43.8
O_3-1-1	Ohtadai	Siltstone	1.554	41.7
O_3-3-1	Ohtadai	Silty sandstone	1.586	39.5
O_3-4-1	Ohtadai	Silty sandstone	1.490	42.9
K_1-1-1	Kiwada	Siltstone	1.449	45.0
K_1-2-1	Kiwada	Silty sandstone	1.483	43.7
K_2-1-2	Kiwada	Silty sandstone	1.608	36.1
K_3-2-1	Kiwada	Siltstone	1.449	44.0
K_4-2-1	Kiwada	Siltstone	1.535	42.4
K_5-2-1	Kiwada	Siltstone	1.472	44.3
K_6-1-2	Kiwada	Siltstone	1.433	45.3

Fig. 1 shows the pore size distribution of samples. The peak diameters of siltstones (both Ohtadai and Kiwada layers) are around 0.1-0.4µm. The siltstones are bathyal deposits and their particle size is rather uniform. On the other hand, some sandstones have two peaks. These sandstones were deposited by turbidity current and most of them are well grained.

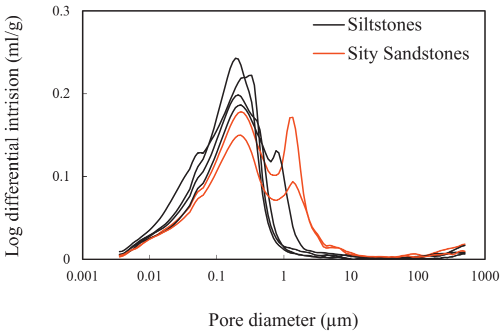

Fig. 1(a): Pore diameter distribution taken from Ohtadai layer

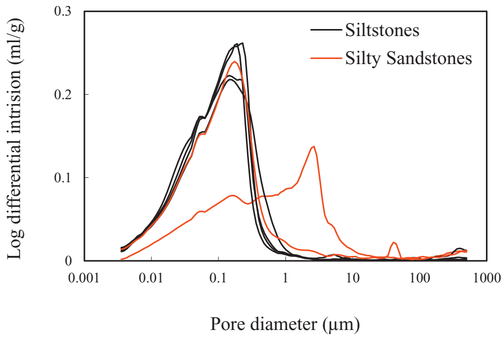

Fig. 1(b): Pore diameter distribution taken from Kiwada layer

3. Test apparatus for measuring threshold pressure with supercritical CO2

To measure threshold pressure using super critical CO2 directly, we developed special test apparatus (Fig. 2). Core holder, which can withstand cell pressure up to 50MPa is set in an incubator to keep temperature constant during threshold pressure measurement. The pressure of CO2 injected is controlled by a syringe pump and pore pressure is kept constant by two back pressure regulators. We use two back pressure regulators so that the back pressure fluctuations due to the amount of outflow become smaller. Water produced from rock sample is measured by electronic balance system located in incubator.

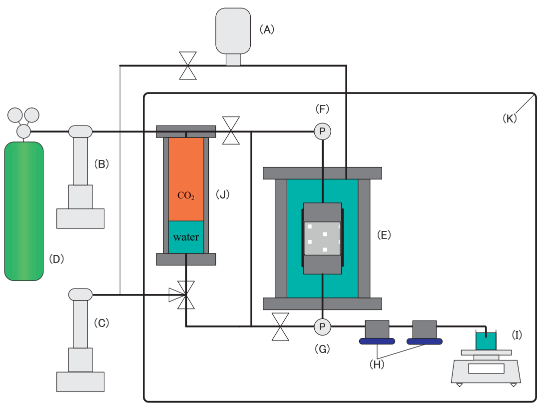

Fig. 2(a): Scehmatic view of the test apparatus for measuring threshold pressure. (A) Accumulator; (B) Syringe pump for CO2; (C) Syringe pump for water; (D) CO2 tank; (E) Core holder; (F) Pressure transducer for upstream side; (G) Pressure transducer for downstream side; (H) Two back pressure regulators; (I) Electronic balance; (J) Buffer tank; (K) Incubator.


Fig. 2(b): Photograph of the test apparatus for measuring threshold pressure.

4. Test method

4.1. Preparation of samples

All core samples were shaped in 5cm diameter and 5cm height using electric cutter and trimming knife in laboratory. Then the samples were put in a tank filled with water and vacuumed for several days. The rest parts of samples were shaped in one centimeter cube for mercury intrusion test (MIT). The cubic samples were dried by vacuum-freeze drying method.

4.2. Direct threshold pressure measurement

Installation of a sample was conducted in a de-aired water tank so that sample was not exposed to the air and the saturation of sample could be kept in almost 100%. For the test with N2, test was conducted in the constant temperature room (approximately 21°C room temperature). Confining pressure was applied to the sample. Due to the confining pressure, consolidation occurred and small amount of pore water in the sample was squeezed out. Drained water from the sample was measured with the electronic balance. When consolidation of the sample was finished, absolute permeability test was conducted by constant head method with water. Darcy's law was used to calculate the absolute permeability of sample. For the test with supercritical CO2, core holder was set in the incubator. After installation of core holder, the temperature in incubator was controlled at 40°C. Confining pressure of 15MPa was applied to the sample and pore pressure of 10MPa was applied to ensure that CO2 was in supercritical state during the test. Absolute permeability of the samples was also determined by constant head method with water. After permeability test, threshold pressure measurement was conducted with gaseous N2 or CO2 in supercritical state. When displacing fluid was reached to the surface of the sample small amount of water production occurred until capillary pressure balance to the injection pressure. When the no water flow was observed for at least 4 hours, injection pressure was increased to the next level. Increment of each steps were from 0.1 to 0.2MPa. This procedure was repeated until continuous flow is observed.

5. Results

Test results are summarized in table 2. Porosity measurement by buoyancy method, absolute permeability test and MIT were conducted for all samples.

To estimate threshold pressures in N2/water system by MIT, two methods are used. By first method, threshold pressure is estimated by the pressure at 10% mercury saturation [2]. From second method we drew the tangent line with minimum grade against the curve relating saturation and capillary pressure. The tangent line is spread to S=0 and this intercept means the estimated threshold pressure (Fig. 3). To calculate the threshold pressure in N2/water system from the result of MIT, we assume that interfacial tension of N2/water system is $72mNm^{-1}$ and contact angle of N2/water system is 0 degrees (the interfacial tension of mercury is $480mNm^{-1}$ and contact angle of mercury is 140 degrees). Direct measurements of threshold pressure with N2 and CO2 were performed using samples of K_6-1-2. Fig. 4 shows the relations between permeability and threshold pressure. There is an inversely proportional relation between the threshold pressures and the permeability coefficients in logarithmic scales and the results in this study are consistent with existing data. Fig. 5 shows the test result of direct threshold pressure measurement with N2. After injection pressure reached 1.71MPa, continuous water flow was observed. We evaluated the threshold pressure as average value between the pressure when continuous water flow occurred (1.71MPa) and the pressure in former step (1.60MPa). From the test result, threshold pressure is evaluated as 1.66MPa. Fig. 6 shows the test result of direct threshold pressure measurement with CO2. Threshold pressure is estimated as 1.00MPa (average value between 1.05MPa (continuous flow step) and 0.95MPa (former step)).

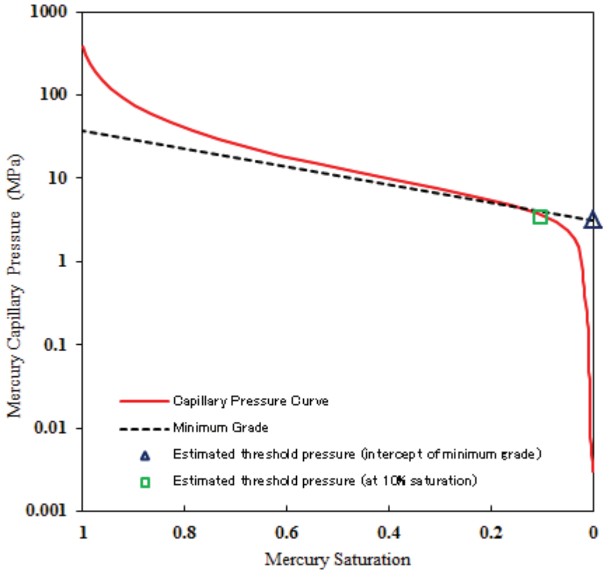

Fig. 3: Capillary pressure curve for K_1-1-1

Table 2. Test result

Sample No.	Absolute permeability (mD)	Threshold pressure (MPa)				
		MIT (Hg/air)	MIT (N2/water) 10% Saturation	MIT (N2/water) Minimum grade	Direct measurement (N2/water)	Direct measurement (CO2/water)
O_1-1-2	7.83E-03	3.36	0.657	0.608		
O_1-2-2	3.56E-03	2.78	0.545	0.483		
O_1-3-2	4.03E-03	1.45	0.284	0.296		
O_2-2-3	2.65E-03	3.06	0.600	0.513		
O_3-1-1	2.01E-03	2.53	0.496	0.592		
O_3-3-1	1.37E-02	0.683	0.134	0.222		
O_3-4-1	2.48E-02	0.749	0.147	0.172		
K_1-1-1	2.35E-03	3.35	0.656	0.619		
K_1-2-1	4.27E-03	2.54	0.497	0.645		
K_2-1-2	2.72E-02	0.340	0.068	0.056		
K_3-2-1	2.10E-03	5.86	1.15	0.942		
K_4-2-1	8.32E-04	1.44	0.282	0.734		
K_5-2-1	1.84E-03	4.43	0.868	0.758		
K_6-1-2a	2.50E-03	4.87	0.953	0.799	1.66	
K_6-1-2b	1.51E-03					1.00

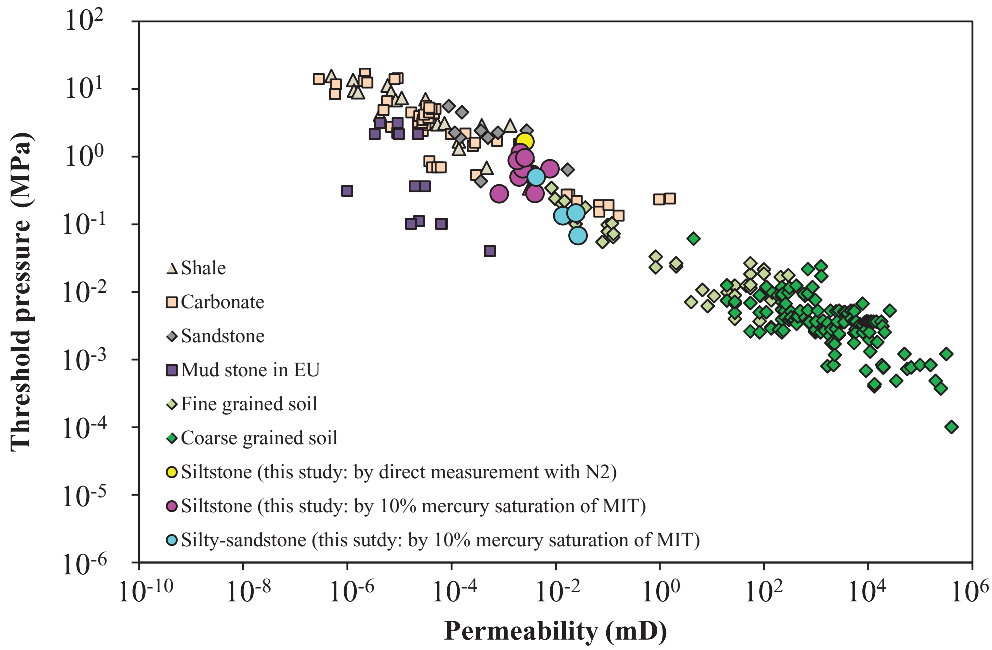

Fig. 4: Relations between Permeability and threshold pressure (referred from Kameya et al [1])
(The threshold pressures are in N2(Air)/water system)

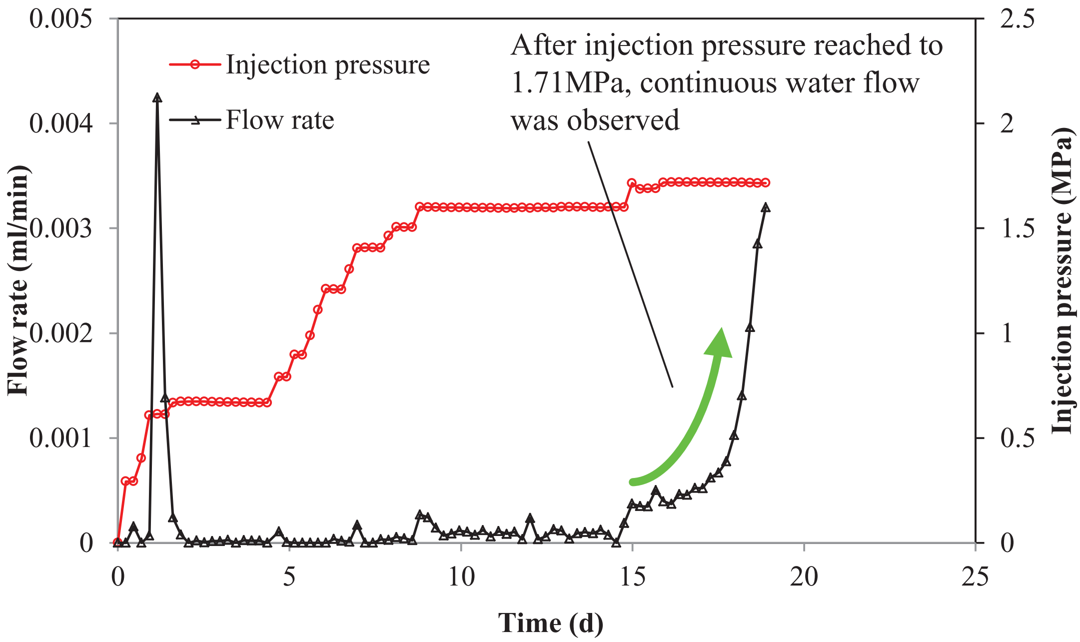

Fig. 5: Test result of direct threshold measurement with N2.

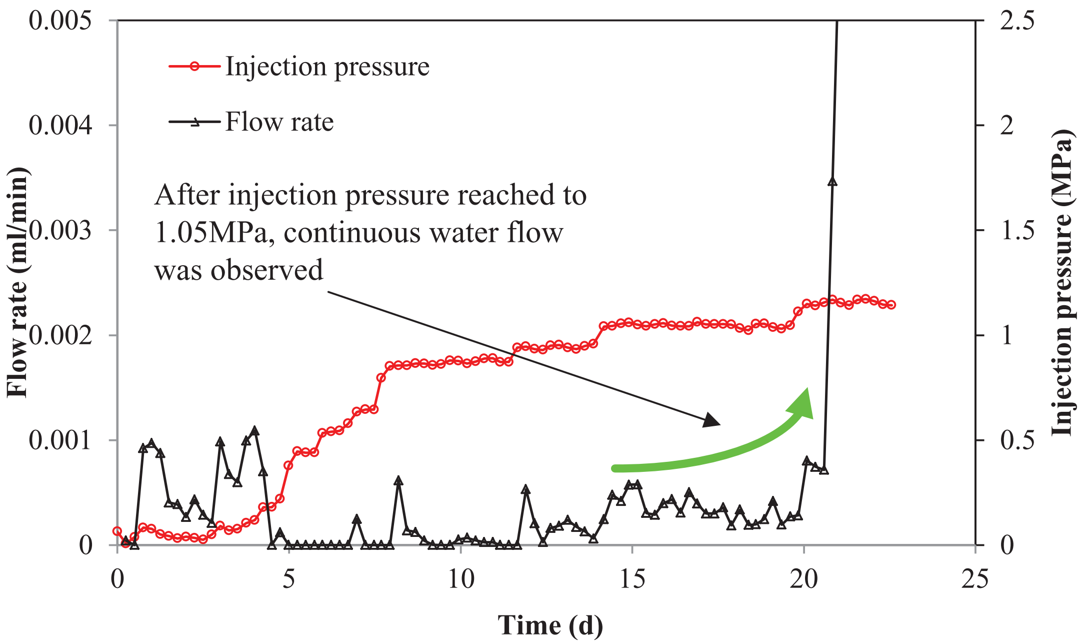

Fig. 6: Test result of direct threshold measurement with supercritical CO2.

6. Discussion

6.1. Threshold pressure estimated by MIT and direct measurement method

From our tests result, the threshold pressures estimated by MIT were lower than those by direct measurement method. One reason of this difference may be caused by the difference of flow direction between two methods [3]. It is well known that the permeability coefficients parallel and perpendicular to the bedding plane are different. This mechanism may affect the threshold pressure value, thus MIT which cannot take account of injection direction may underestimate sealing capacity of laminar rocks.

6.2. Threshold pressure measurement with N2 and supercritical CO2

For estimating sealing capacity, threshold pressure measurements with N2 are usually used because this test apparatus is rather simple, but there are not so much threshold data with CO2. Li et al [4] conducted threshold pressure measurements with 3 kinds of gas (N2, CH4 and CO2). They reported that the threshold pressures are almost proportional to the interfacial tensions of the gas/water systems. In their study, N2 threshold pressures are 2.65-3.03 times higher than those of CO2. In our study, N2 threshold pressure is higher than CO2 threshold pressure. This tendency is consistent with their result. However compared with their result strictly, the ratio between N2 and CO2 threshold pressures is slightly smaller. In our study, the permeability coefficients of N2 and CO2 samples have small difference. To discuss the threshold pressure ratio precisely, more test results might be needed.

7. Conclusion

1. There is the inversely proportional relation between the threshold pressures and the permeability coefficients in logarithmic scales and this relation is consistent with pre-existing data.
2. Threshold pressures estimated by MIT may be underestimated because MIT can't take account of the flow direction.
3. Threshold pressure with N2 was higher than the one with CO2. This result is consistent with the report by Li et al. [4].

8. References

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